International Journal of Disaster Risk Reduction 30 (2018) 235–243

Contents lists available at ScienceDirect

International Journal of Disaster Risk Reduction

journal homepage: www.elsevier.com/locate/ijdrr

Assessing and mapping urban resilience to floods with respect to cascading effects through critical infrastructure networks

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ARTICLE INFO

Keywords:
Urban flooding
Critical infrastructure networks
Cascading effects
Resilience strategies
Climate change

ABSTRACT

The urban environment is very concerned by network failures. These failures are propagating risks in area generally considered as non-vulnerable. There are various causes of possible disruptions in critical infrastructure networks (CIs), such as natural hazards, technological hazards, accidents, human errors and terrorism. However, in the last years it became harder to identify the possible failures of complex networks and to forecast their effects on the urban environment. New challenges such as climate change and the ageing of CIs are likely to increase the difficulty to secure the lifelines, raising the potential of damages and economic losses caused by failures. This paper suggests some new methods to assess and map resilience levels to floods taking into account critical infrastructure networks as risk propagators at different spatial scales. The conclusions support the development of innovative strategies and decision support systems for new resilient urban environments.

1. Introduction: Human-made disasters and cascading effects

In a global changing – and warming – context, natural disasters have increased of about 2% a year in the world over the past 15 years [7]. Summer 2017 is a representative example of the accumulation of natural disasters in a very short period of time. Mid-August 2017, Hurricane Harvey reached Caribbean and Texas. This category 4 hurricane (out of 5) caused more than 80 deaths and heavy economic losses in this oil region, with many days of torrential rains. The Gulf of Mexico did not really have time to recover: Irma breaks after Harvey, with winds of more than 290 km/h. This category 5 hurricane almost completely destroyed the French islands of Saint-Martin and Saint-Barthélemy. The damage costs were estimated at 1.2 billion euros by the *Caisse centrale de réassurance* (CCR) [6]. Mid-September, Hurricane Maria reached Dominica, eastern Caribbean (two weeks after Hurricane Irma), northeast of the Bahamas and Puerto Rico. It caused a hundred deaths and the damage costs are estimated between 15,9 and 95 billion dollars. This accumulation of disasters in a very short time period highlights a global climate deregulation [23]. If those examples remain extremes, we observe an increase in the "daily disasters".

Among these disasters, the risk of flooding causes the most destructions [46]. Indeed, since 1960, the number of floods has increased considerably, reaching more than 600 events for the year 2007 [48]. For example, in 2013, we observed that flood damages were approximately 50% higher than in the period 2003–2012 [33]. Although the number of deaths has decreased in the face of this risk, floods are still the costliest natural catastrophe, with a total volume of 100 billion €/year by the end of the century.

At the same time, the increasing complexity of cities makes flood risk management difficult. Over the last ten years, half of the world's population has become urban. Human concentration (50% of individuals living in urban areas [48], and urban population makes flood risk management very difficult in such areas. Urbanization of urban areas has increased from 10% in the 1990s to 50% in just two decades [24]. This very rapid process has weakened the territory because cities are not prepared or equipped to manage the needs of such a concentration of population, especially when a risky situation appears. This, due to a lack of available land, comes to settle in the risk zones. These spaces left free are gradually nibbled by urbanization without respecting the natural functioning of catchments, rivers… leading to impervious soils, preventing the necessary infiltration of rainwater. Also, the increase of man-made disasters - an increase in frequency and intensity - makes these territories even more fragile and complex to manage. It is therefore established that, in urban areas, man-made risks tend to have extreme consequences [30] especially because issues are concentrated in vulnerable areas. Besides, these areas are increasing because of urban sprawl.

Among the urban equipment, some infrastructures are more essential than others, namely Critical Infrastructure (CI). It is a hard task to define what "critical" infrastructure exactly means. Etymologically,

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https://doi.org/10.1016/j.ijdrr.2018.02.018
Received 29 October 2017; Received in revised form 11 February 2018; Accepted 12 February 2018
Available online 15 February 2018
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critical comes from ancient Greek *kritikos*, word linked to the vocabulary of crisis, derived from the verb *Krinein*, meaning “separate” or “decide” or “choose” [38]. These infrastructures concentrate all the functions [32] which are necessary for the functioning of a community. They are considered as “critical” because their potential destruction could weaken the whole defense and economic organization [16] of a country or a city. Critical Infrastructures can be natural; water supply, flood water storage; built, energy networks, telecommunication networks, emergency services, transport networks; or virtual, cyber information systems for instance [16,38]. Nevertheless, none exhaustive list exists to explain what is a critical infrastructure.

Cities are developing links between people, activities, properties, infrastructures and networks and create by this way a quality of life and dynamic activities. However, the density of urban creates new risks. The lack of available lands results to build new infrastructures in risk areas [38] and, moreover, this sprawl leads to an over-interconnection between technological networks and society. These links have increased the vulnerability of urban areas, building an interdependence [32] between all urban factors. The complexity of infrastructures and urban systems weakens the functioning of components in a time of crisis. Because of the interconnected system, if a shock happened, the system would crash more often since the dysfunctional phenomenon would be more important than the first affected area [38]. It appears that, the more a territory is connected, the more the impacted area will be important [22]. Because of the concentration of activities, networks and populations, the spread of risks is very quick and disrupts large-scale territories. The main difficulty is that experts cannot precisely predict the potential breakdown of infrastructure or its domino effects [33,5]. As we cannot predict these events, traditional crisis management is ineffective in case of infrastructure breakdown [5]. Prevention and planning management are not suitable in the way that these strategies do not take into account the dynamics of threat, and therefore the dynamics of interdependences [38]. But the very own definition of crisis and its consequences, is that its unpredictable, in permanent changes and evolutions. That's why, for more than ten years, experts have begun to question themselves about their risk management. In policy, economics, urban planning, architecture and scientific research the focus is now increasingly focusing on strategies to make urban systems simultaneously less vulnerable and more resilient to climate-related disasters, while addressing the long-term challenges of sustainability and quality of life [34]. The injunction of international authorities to find a new risk management (system) able to create a transition to a general culture of risk [14] led researchers and managers to look at other approaches to manage natural hazards. A new approach has thus been gradually integrated, based on the concept of urban resilience.

The goal of this article is to present new methods, in a way to better understand urban risk propagation through CIs breakdowns and to reduce vulnerability of network interdependencies increasing urban environments resilience. We will define in a first part what “cascading effects” and “risk propagation” exactly mean. In a second part, we will describe how we used the concept of resilience to design some methods and tools, thanks to a research-scientist collaboration and managers of the territory, to improve the resilience of urban environment to floods. Finally, we will present two possible applications in Hamburg (Germany) and Avignon (France).

2. Cascading effects and risk propagation

Globalization created a connected world, an imbroglio of policies, economies, procedures and expectations. These interactions between territories and societies are complex and create interdependencies [38]. However, these interdependencies create as much wealth and security as they weaken the territories and their populations in case of risks. As urban areas are interconnected, an infrastructure breakdown will impact territories beyond geographical and functional borders [5]. As they are connected and dependent on multiple levels, CI may impact much more than their first impact territory. The evolution of the impacted area can be caused by cascading effects, effects which increase the impacting area, generating secondary effects [32]. For example, urban networks can increase the risk, propagating water into large areas. Major floods can impact a specific area but as networks are interconnected, the risk will reach other territories which should not be flooded [22];. Besides, some crisis consequences are not caused by physical and direct damages but by the interruption of activities. Failure of electricity system can damage perishable goods, road deterioration can prevent relief from reaching an area, aggravating the danger of the populations, and complicate first responder operations.

Urban networks failure is a good example to understand and measure what a breakdown of CI can be. Urban networks are an essential part of the urban system. In an interconnected world, urban networks connect more and more people and territories, offering an important variety of resources and opportunities but also creating complex situations of interdependence. Public transport, electricity networks, gas, telephone, heating, waste, etc., make the urban system management more complex and delicate [38]. If they are essential to create dynamics, relationships, economies, these networks are also extremely vulnerable. Because of their interconnectivity, all urban operations depend on them. A single failure can have cascading effects and impact the entire network and, because of (a) reticular urban system, the entire city.

Consequences of Hurricane Sandy in New York City are a good example of these extreme vulnerabilities aggravated by CI breakdowns. Hurricane Sandy, one of the largest hurricanes ever recorded in the Atlantic [26], emerged off the west coast of Africa on October 11, 2012 and moved over the Gulf Stream. Sandy created a storm surge with highest values in New York City and its harbor, causing the destruction of part of the electricity grid: destroyed air lines, flooding of the buried network, etc. Flood impacts included flooding of subways (Fig. 1; the Long Island Rail Road remained closed until November), road tunnels, and the three major airports.

The New York University Langone Medical Centre was evacuated after the breakdown of generators due to flooding, causing the transfer of 200 patients. The destruction of power networks left 21,3 million people without electricity and the failure of electrical system caused fires which destroyed 111 houses and damaged 20 others [20]. Daily life was severely disrupted, with the interruption of the metro, the breakdown of the heating network, security systems, telecommunication services. In addition, alternative solutions such as emergency power generators have not been able to operate, refineries being in short supply and unable to provide the necessary fuel. If direct damages were estimated at 32,8 billion of repairs and restoration, indirect losses have cost much more for city and citizens. Due to interrelated networks and activities, indirect losses are caused by disruption of CI, such as

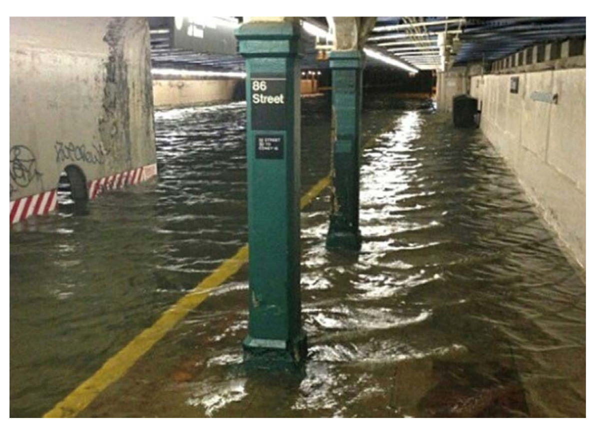

Fig. 1. Port Jefferson, NY.
Source: Newsday

economic losses due to an interruption of economic structures [20]. The balance-sheet of the management of hurricane Sandy is quite bad. The unprepared managers and citizens increased the crisis impacts. For example, the late evacuation order and misinformation resulted in the impossibility of evacuating some institutions. In addition, the crisis highlighted the vulnerability of sewage systems, the poor anticipation of network failures, the lack of a plan B for accessing to generators and relay antennas, and the installation of resistant flood-barriers [21]. In this case, the over-connected territory and society created new risks and made the crisis and post-crisis management harder and more complex.

CI breakdowns also have consequences, even before the event itself. Fearing the recurrence of the hundred-year flood, Paris (City) dedicated 5–9 billion to networks' damages on the 17 € billions of damages expected. The RATP expects that 200 km of tunnels would be flooded and unavailable for years. The supply of water networks would be reduced by 30%, three incineration plants will be closed (while waste generation would be equivalent to three years of production), 320,000 people will not have gas anymore, 48 bridges will be impracticable and 4 highways will be closed. Consequences of this kind of flood will be terrible for the local economy; 3964 commercial locals will be directly impacted and 40% companies located in a food zone will be submerged by 1 m height. Furthermore, the historical patrimony will be impacted, with 3 libraries flooded (François Mitterand library, Institute library and Mazarine library), several museums (Louvre Museum, Orsay Museum, Museum of Natural History and its menagerie, School of Beaux-Arts, etc.). Besides, all the archives (Prefecture, gendarmeries, insurances, etc.) are underground and could be impacted by a flood. All these buildings are classified and contain historical and artistic treasures and their destruction will be an immeasurable and incalculable loss for present times and future generations.

These case studies highlight the problematic of an urban flood and its cascading effects on territory and society. Given the strong interactions that exist between the different networks and the degree of dependence of public services, the least disturbance can spread both from one type of network to another but also, geographically, outside the only flooded area. It is a potential aggravation of the situation for the concerned territory. It is therefore essential to minimize the additional problems that flooding of networks may entail. Because of their interdependencies and vulnerability, territories must be prepared to important crisis and breakdowns of critical infrastructures, especially because these cascading effects are more and more common and expected [29]. But how can we face to theses breakdowns which will lead to cascading effects? These effects are terrible and unpredictable. By definition a crisis is a sudden event, which is neither foreseen nor thought or imagined. We cannot precisely predict a breakdown, its cascading effect and their consequences on territories and populations.

If traditional risk management strategies, such as planning and prevention, are not adapted to face to this unpredictable breakdown, a new kind of urban risk strategy appeared a decade ago, the resilience strategy [5]. This work is defending the idea that a strategy based on the concept of vulnerability and precaution may have many limitations and is not adapted to a visionary policy and management. After defining and defending the concept of resilience, we will expose some examples with resilience strategies.

3. Resilience to cascading effects: From a theoretical paradigm to strategic approaches

Since Hurricane Katrina and its consequences in New Orleans in 2005, the attention of scientists, urban managers and politicians has been focused on the concept of resilience as a new paradigm for the implementation of more integrated risk management in a systemic manner. To avoid the recurrence of such a dramatic episode about 1400 deaths in Louisiana [35] and also costly $ 82 billion [2], experts began to re-question their risk management policy. A new approach has been gradually integrated, based on the concept of urban resilience. This term - from the Latin *resilio* (*re*, back; *salir*, jump) - has gradually been incorporated into scientific and political discourses in order to adapt to the expansive and uncertain growth of urban areas [24]. However, the term resilience is somewhat vague and inconsistent, probably because of its overuse, thus transforming the concept into a portmanteau word or buzzword [36]. If, historically speaking, the concept of resilience appeared in physical field to describe the return to the previous state of an element, it was the field of psychiatry that served to popularize the term. For the psychiatrist Boris Cyrulnik, resilience is a capacity to take back a development despite trauma. It is understood as the ability to withstand a shock, both in resisting and adapting, in order to restore acceptable functioning [11]. Adapting to the ecological field [18], resilience is defined as the capacity of a system to absorb disturbances and to recover after a major disruption and to restart an activity on the territory. The concept emphasizes the idea that disturbance - or shock - is not (or not anymore) necessarily negative, but is fully involved into the creation of a new model by supporting the idea of innovation, learning, rebound and change. The Latin etymology of the term resilience underlines this ability to overcome a crisis. It is thus a proactive capacity that the system must develop in order to (re) act in the face of the catastrophe and develop learning and anticipation abilities [12], accepting by this way the inevitability of change and trying to create a system capable of adapting to new conditions and obligations [19]. The altered system must therefore be able to evolve, adapt, re-establish, maintain or create a balance of functioning. Resilience refers to capacity as well as absorptive and recovery capacity [38], to a learning ability [45,47], or adaptability capacity [39].

This work considers that resilience is intrinsic to the environment, that it is inherent in the internal functioning of the system. There is then not necessarily a need for a shock to be resilient, this capacity can be pre-existing to the crisis. However, this quality can be revealed by the shock. Resilience factors can therefore be identified a-chronically so as to study and develop the potential for resilience [36]. Resilience term always refers to a return to an acceptable equilibrium, whether pre-shock or new one. Therefore, it is a concept that refers to a technical, urban, social, architectural, economic and political innovation and that allows a questioning of our risk management systems. This injunction to innovation adapts perfectly to the urban, economic, political, social and ecological complexity of the contemporary and urban world.

However, despite the significant increase of the use of the term resilience [24] in urban practices, concrete advances still have to be made. The majority of nowadays' work is essentially based on a technical-organizational resilience but without taking into account its social dimension. The objective is therefore to facilitate the understanding of this concept, and especially its integration in management and planning policies, at the crossroads of urban, technical and social resilience. This work aims to operationalize resilience by creating a spatial decision support tool that would integrate the theoretical concept into urban practices and flood risk management policies to decrease negative impacts of flooding and its potential cascading effects. Our proposal is divided in two parts, one work already achieved, proposing a technical approach and acting on urban networks, and a current work – part of a research thesis – in order to build a global resilience approach. These two kinds of approaches are built as a continuum.

3.1. Urban resilience strategy

Urban resilience is on the one hand, the capacity of a city to maintain functions during crisis and on the other hand the capacity of the city to reconstruct itself after disturbance [22,44]. The city is considered in this case as a complex system, integrating the components and interactions of inhabitants, activities, infrastructures, governance, uses, habits, etc. Toubin et al., [44]. If there is no one and only definition of the city, it is mainly because the city is linked to its society, evolves and changes with it and, therefore, is not a static element [44]. Indeed, the city is a space, perceived, lived, understood, thought by its

citizens and practitioners. Cities are a complex combination between history, natural conditions, economic activities, urban and architectural management, and political policies. However, urban management strategies have to handle this complexity, in order to offer a living environment that is adapted and safe. The increasing concentration of populations in cities, associated with the rise of natural risks, makes this urban management even more complex. The change in cities – new actors, new interdependencies, new infrastructures, new dependencies, new activities, economies, relationships – associated with new urban vulnerabilities – pollution, infrastructure breakdowns, social tensions, space tensions, political tensions – create new kinds of risks and require another way to manage these weaknesses.

3.2. Analyzing risk areas

In order to build a strategy of resilience, it is necessary to define which elements make resilience and which urban elements are vulnerable and able to create domino effects. Many studies have examined which, in the urban area, was more or less resilient and which characteristics increase or decrease resilience factor.

3.2.1. A technical approach

As we already mentioned before, urban networks are able to propagate flood risk [22,41] and to increase territory vulnerability. They are simultaneously the "entry point of risk" and essential for the management at the very first moment of the crisis and in the reconstruction phase. A city is a kind of crossroads, where all functions and activities hang out. Thus, if urban networks can be synonymous with wealth by transferring goods and populations, they can also be a source of vulnerability by propagating disturbances because of their interdependences [44]. They seem so necessary to build a resilient city. Three capacities have been analyzed in this study, in order to characterize the resilience of urban networks, and developed into the DS3 Model [2,3,38,40]; resistance, absorption and recovery capacities (Fig. 2).

Resistance capacity is considered as the beginning for all resilience studies. The goal of this step is analyzing physical damages [41]. To begin with, it is essential to know any risk management and actions, to plan the potential damages of a system, in order to adapt resilience strategy. It is estimated that, the more the technical system is damaged, the greater is the possibility of a malfunction of the system and the more it will be difficult to restore it to service. The operating reliability methods are used in this case, in order to take account of the interdependencies between the different networks producing domino or cascading effects.

Absorption capacity includes potential alternatives which networks can have, despite of failure of one or more of its components [22]. In other words, analyze network's configuration is a way to characterize its redundancy.

Recovery ability can be the time required to restore one of its damaged components to normal service. It appears as the main resilience characteristic [38,41]. In this case, recovery does not mean that system must return to a previous equilibrium but that it should find a new mode of operation [38].

This conceptual model is considering cities as complex systems and integrate several notions of resilience. It includes the urban systemic model for the propagation of flood risk in the city by protective infrastructures and technical networks and resilience concepts as redundancy (capacity to absorb risk) and rebound (recovery capacity). Besides these characteristics, the resistance capacities of infrastructures are added to the evaluation of resilience.

3.2.2. A holistic resilience approach

This precedent study is focused on the technical aspect of resilience. Our current research is concentrated on multiple social and territorial dimensions which could increase or decrease resilience. As we defined it before, resilience is still considered as the ability of a community and its territory to plan for, absorb, recover from, adapt, learn and evolve despite – or thanks to- a shock. But evaluating a resilience proportion is not so easy. In this particular case, we understood resilience as inherent capacities, which we may be able to study without a specific shock. This philosophy has allowed to analyze interactions between human, urban environment, technical environment, political environment systems [8].

Over the last decade, more and more indicators have been used in the risk research, and more precisely to measure vulnerability of territories and populations at risks [9]. A vulnerability indicator can be defined as a tool able to provide data about susceptibility, fragility, vulnerability, adaptability and resilience of a system [15,4]. Some choices of indicator methodology and their construction have been made based on the hypothesis that vulnerability and resilience are linked [10,42,8]. In this research we developed variables in order to study both inherent vulnerabilities and inherent resilience of a society and its territory. It is established here that these variables indicate a *potential* for resilience in order to revive a social, economic, urban, and systemic activity after a shock. A resilience index was therefore

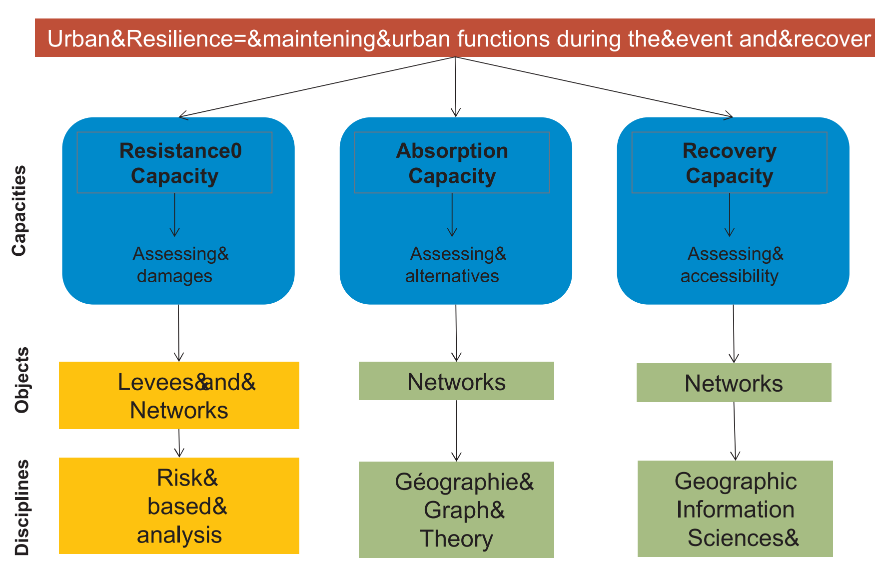

Fig. 2. DS3 Model representation [38].

Table 1
Variables sources.

Indicators	Variables	Sources
Social'Indicator	• %'of'active'people • %'of'women • Age'of'population • Highest diploma • Median of'salary • Vulnerable population • Etc.	INSEE'
	• Risk knowledge • Risk perception'	Social'questionnaires
Urban Indicator	• Critical infrastructure • Urban density • Aging of'buildings • Etc.	INSEE,'Avignon's data
Technical Indicator	• Urban networks • Aging of'networks • Etc.	INSEE,'Avignon's data

Fig. 3. Resilience variables.

constructed on the basis of three indicators of urban, social and technical resilience. The choice of a hierarchical index [42] was justified by the possibility of creating indicators with several variables (Table 1), themselves divided into subgroups (Fig. 3), so as to nuance the interpretation of resilience. The variables of each indicator were based on an analysis of the scientific literature [1,10,13,22,28,31,37,40,42] in order to analyze the different social (age of the population, level of education, knowledge of risk, etc.), urban (urban structure, economic dynamics, state of structures, etc.) and technical components of the territory. The scientific consensus that resilience is multidisciplinary has led to the selection of data including the social, economic, institutional, infrastructure and community structure [37,9]. Thanks to the indicators' methodology, it is now possible to explore social, urban, technical phenomena and to determine which area is more or less resilient by a comparative work [27].

Then, each variable is placed on a positive or negative curve of resilience. This definition of the parameters corresponds to a unique form of deviation [17] for each variable, thus making it possible to vary the overall value of the resilience per indicator. If the value of the resilience curves is different for each variable, the weighting is 1 for all variables. This choice of single weighting is explained by the desire to avoid disparities between the variables, some of them being sensitive and subjective (% of foreign people, level of education, etc.). In order to create a generic tool that can be used by different actors, all the indicators are built using national data in Open Data (INSEE or SIREN) and Open Source. The resiliency calculation for each variable and indicator is built using a Data Management Engine (ETL), the Feature Manipulation Engine, used by the GIS service of French cities. Maps and analyses are done on QGIS. The spatial scale of analysis is local and (is) explained by the desire to work with local actors in order to answer precisely to their problems of management facing the risk of flooding. Thus, urban projects at the neighborhood or macro-lot levels will be analyzed in terms of their contribution to the intrinsic resilience of the neighborhood. This scale of neighborhood or urban project, so far little practiced [2] allows to act directly on the territory, to innovate, to experiment and to test new practices [3] directly with the managers. As a result, the main scale of study chosen to assess urban resilience is as accuracy as possible, i.e. at the IRIS scale. This scale is located between the 200 × 200 grid (INSEE) and the District Council. Each computation is therefore multi-scalar but also multi-temporal. Indeed, the resilience to risks must be imagined according to a multi-temporal paradigm, to act before the crisis, i.e. to anticipate (urban planning); and to recover from the event (to rebuild, to restore an activity, to adapt).

The technical approach emphasizes the importance of taking into account critical infrastructure, and more specifically urban networks facing flood risk. Focusing on the impacts of potential dysfunctions of urban networks at neighborhood scale was an innovative approach because of the capacity to determine the level of resilience of a neighborhood from a technical perspective. Offering a conceptual tool for neighborhood-level resilience analysis (DS3), this approach defined and developed three resilience characteristics. Thus, by defining and operationalizing resilience, this analysis tool makes it possible to identify resilience characteristics at the neighborhood scale.

Even if this approach is innovative, its analysis is limited. Considering that the urban system is an evolving, changing and dynamic system, with an urban renewal of about 1% every year, analyzing resilience characteristics only via urban networks in new neighborhood

remains reductive as it is considering only small areas compared to city size. To complete this approach with a holistic approach for resilience assessment is currently in progress. This holistic resilience assessment aims at assessing level of resilience to risks including social, urban and technical (based on the development of the DS3 model) indicators. Our hypothesis here is that the holistic resilience assessment could help to define resilience strategies at several spatial scales, including historical neighborhoods. Also, analysis of resilience with this approach could measure how resilient to flood new neighborhood development can contribute to resilience to floods at other spatial scales. This is what we are testing in the Avignon case study.

4. Applications in Hamburg and Avignon

These two different approaches, technical and holistic approaches, have been built as a continuum. Our work started by the application of the technical approach, especially in Hamburg. After the introduction of this case study and its results, we will present our current work, built in the continuity and thanks to the observations and limits highlighted by the technical approach. This work, constructed as part of a thesis, presents a more global approach to resilience.

4.1. DS3 at neighborhood scale: Am Sandtorkai / dalmannkai, Hamburg

The DS3 model has been tested in a neighborhood of Hamburg in the Northwest of HafenCity in order to build an attractive living environment. The Am Sandtorkai / Dalmannkai neighborhood is a dense urban area, with a young population co-existing with seniors. As it is outside the Hamburg's dike line, this area is subjected to flooding [38]. Affected by storm surges up to 5 or to 6 m [38] and pluvial floods, Hamburg, and specifically this neighborhood, is vulnerable. The neighborhood is vast (about 10 ha) and its density is 137.61 inhabitants per hectares. This area is connected with the city by 4 bridges, but only one of them is flood-secure. However the neighborhood developed several modes of transport; "soft" modes of transport as bicycle, and has integrated the flood risk, building roads above the flood-line reference [38]. Based on the three resilience characteristics, resistance, absorption, recovery capacities, some characteristics have been defined as increasing resilience ability of the neighborhood or not.

The diversity in transportation – public, soft, private modes and particularly urban networks above the higher reference water level - connecting the neighborhood to the entire city is a good element to develop and increase resistance, absorption, and recovery capacities. Develop and mix energy supply (renewable energy source for instance), promote the multi-functionality of buildings, integrate the water level reference in every construction, are also aspects which could increase resilience (Fig. 4).

The contribution of the use of DS3 Model identified factors that would lead to increase urban resilience, highlighting the importance of urban networks and critical infrastructure. However, this technical approach is essentially focusing on urban networks. But cities are composed by many factors, as social dynamics, urban interactions and technical components. The holistic approach is based on the building a methodology in order to study these components, and answer to these global issues.

4.2. Mapping urban resilience

The holistic resilience research has been built with the Avignon community, in Provence-Alpes-Côte d'Azur (PACA) region, in order to concretize the theoretical approach. The City, faced with physical (Rhône-Durance rivers confluence) and human tensions, needed a decision-making tool to integrate the concept of resilience into practices. This is carried out in partnership with the urban and technical services of Avignon. Indeed, even if the city is already equipped with communication and protection tools (Flood risk prevention Plan (PPRI), Plan to determine territories with flood risks (TRI), Municipal information document on major risks (DICRIM)), the concept of resilience is, as stated earlier, still very little developed. A decision-making tool to integrate this concept with urban practices would be extremely innovative and useful for a community vulnerable to flooding. This collaboration enriches the theoretical work of research by integrating it more closely with the social, urbanistic, architectural, political and economic needs of the community. It is therefore a work at the frontier between practical and professional application and theoretical research. Preliminary results illustrate an independent resilience of a specific flood scenario. The indicators allow to independently map each variable and each indicator (Fig. 5, Fig. 6), but also to condense them to create an overall index of resilience. Fig. 5 has been built thanks to social resilience variables, as population structure data (age of population, INSEE data); professional situation (INSEE data); habits (INSEE data); education (INSEE data), etc. These variables have been aggregated in order to map a global social resilience indicator for a scenario "during crisis". (The) Fig. 6 has been built on urban resilience variables such as buildings' characteristics (construction date, SIREN data), location of critical infrastructures (SIREN data), economic dynamic (business creation and closure, SIREN data), etc. These variables have been also aggregated in order to map a global urban resilience indicator for a scenario "during crisis". The local scale chosen as well as this dissociation between variables and indicators makes it possible to analyze precisely the components that accentuate or diminish the resilience.

Even if these maps have been designed according to the different temporalities of a crisis (before, during, after), the flood hazard (water levels, rainfall, etc.) has not been integrated into the calculation (as a physical component). It is therefore an objective resiliency that is represented here, independently of a specific risk. Despite the fact that calculation parameters were created in relation to a temporality (before, during and after the crisis), the physical and geographic components (width of the catchment, land cover, vegetation cover, etc.) have not yet been included in the calculation. A hazard indicator has been created, but it is still necessary to work on different simulations by integrating the spatial (spatial risk) and temporal (flood duration, flood and flood) parameters. Finally, with the idea of measuring the existing resilience but above all the impact of future floods on the dynamics of the city, it was interesting to locate spatial projects spatially during the period 2015–2020. These are as varied as the rehabilitation of some roads, as the creation of a tram line or new eco-neighborhoods, but each of them participates in a structural and landscape renewal of the city. These projects are to date simply spatialized in the resilience maps but are not yet integrated into any calculation as an independent variable. A selection of key projects (large-scale urban projects) is also underway.

Being able to measure urban resilience variable by variable helps to determine which urban, technical (critical infrastructure) and social (population structure) elements are enough resilient or not [25]. As a result, city management will focus on developing less resilient elements so as to increase the resilience in the long term.

5. Conclusion and perspectives

The international examples of urban disasters and their cascading effects demonstrated the significant modern challenges of urban flood management, especially in an uncertain context. In the urban context, it is also an innovation to build an urban resilience strategy. While the concept of resilience still remains vague and imprecise in many aspects, the international work of the various researchers and risk managers succeeds in allowing us to perceive characteristics that a territory must develop or acquire in order to be resilient and to face risks. The concept of resilience provides interesting answers to take into account complex and multi-scale systems such as the city and its technical networks.

The described case studies have been chosen to emphasize the capacities of preparation, resistance and adaptation, capacities that are

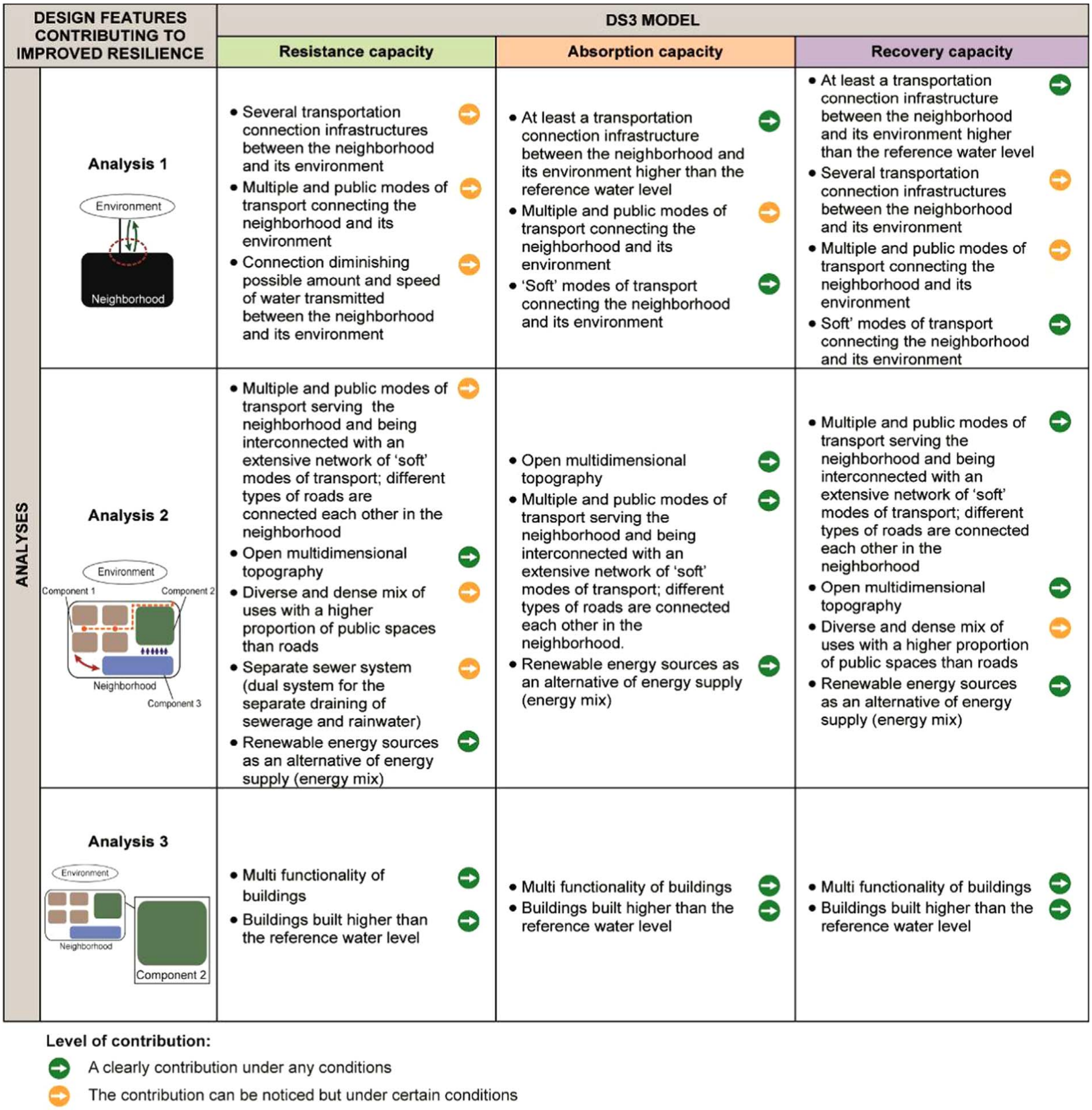

Fig. 4. Synthesis of study results [38].

declined according to the different temporalities of a flood. These studies thus developed an analysis adapted to the multi-temporal form of a crisis but also to an accurate spatial scale. Moreover, these researches have sought to develop a science – policy dialog with territorial managers, to integrate the concept of resilience into public policies and automatisms. By these works, we analyzed both technical resilience by measuring capacities of the technical systems to resist, to absorb then to recover from a perturbation and global – or organizational- resilience highlighting which urban factors were able to enhance or decrease resilience. The application of these strategies to specific territories demonstrates their feasibility and usefulness in so-called risk territories. In addition, the research-practice partnerships underline the growing need for territories and communities to acquire tools in order to better understand the concept of resilience, and especially to apply it practically to their territories, habits, populations, operating modes, knowledge and perspectives. For example, the city of Avignon already uses the new social resilience database in order to study the urban well-being and quality of life at a local scale. With these new data, the city is planning to create a decision support tool to influence urban renewal projects to analyze the quality of social and urban life. In addition, an order has already been made by the Director General of Services (DGS) of the city of Avignon to the GIS service to create a demographic and social atlas on the community, thanks to the new data provided by the research work.

Combining these results should be interesting to understand globally urban resilience and to build a strategy to increase urban capacities to face floods. Finally, it would be interesting to provide a comprehensive index on urban resilience, an index that makes sense in the international approaches [43]. The importance given to the generic nature of the tools allows testing the urban resilience tool or index elsewhere. The holistic approach should be carried out in La Rochelle (France), Mons (Belgium) and Québec (Canada). Since the objective is always to use open source data, in order to make the tool accessible and useful for all types of future users, it would be interesting to test this methodology in other cities in various contexts and observe if same data are available. Thus, the systemic comparison of resilience will shed

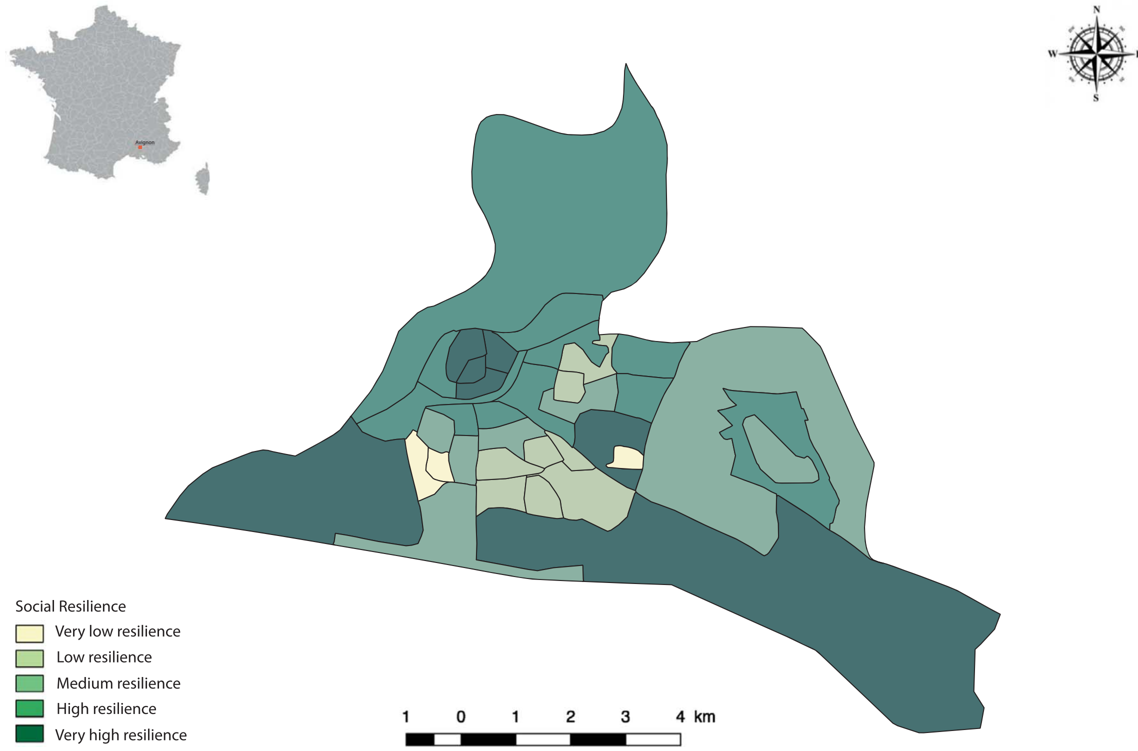

Fig. 5. Social Resilience Mapping - Scenario During Crisis.

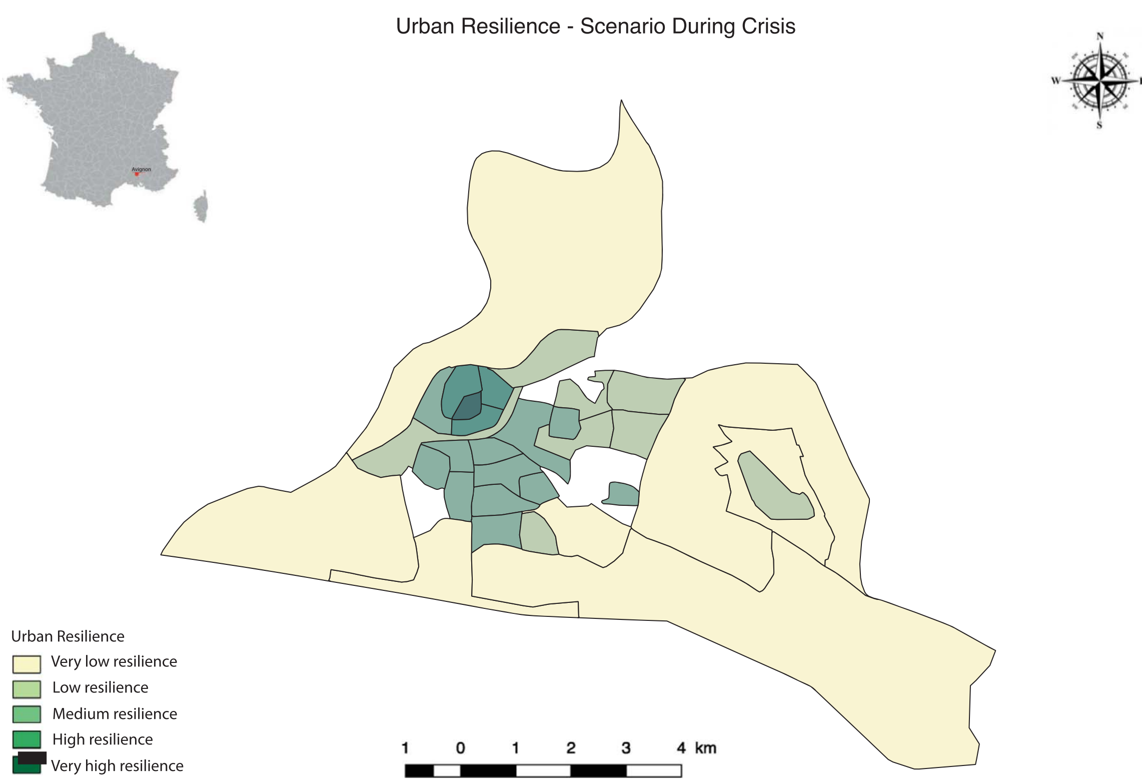

Fig. 6. Urban Resilience Mapping - Scenario During Crisis.

light on the limits of results and work towards their improvement. Finally, to measure the existing resilience and especially the impact of future flood events on the dynamics of cities, it would be interesting to study the resilience impact of future urban projects in the period 2015–2020. Do they increase or decrease urban resilience? This tool would be essential to analyze the impact of urban projects and their involvement in the development of a resilience strategy.

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